Liquid metal based thermoelectric generation system for waste heat recovery

Dan Dai [a], Yixin Zhou [b], Jing Liu [a,b,*]

[a] Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, PR China
[b] Department of Biomedical Engineering, School of Medicine, Tsinghua University, Beijing 100084, PR China

ABSTRACT

A new type of thermoelectric generator (TEG) system based on liquid metal which serves to harvest and transport waste heat, is proposed in this paper. To demonstrate the feasibility of the new TEG system, an experimental prototype which combined commercially available thermoelectric (TE) modules with the electromagnetic pump was set up. Output voltage from TE modules and temperature changes of the main parts (waste heat source, liquid metal heating plate, water-cooling plates I and II) of the liquid metal based TEG system were experimentally measured, as well as the flow rate of cooling water and the load resistance. It was shown that the maximum open-circuit voltage of 34.7 V was obtained when the temperature of the waste heat source was 195.9 °C and the temperature gap between liquid metal heating plate and cooling-water plates was nearly 100 °C. These experimental results obviously verify that using liquid metal based TEG system for waste heat recovery is highly feasible. In addition, the TEG system performance is discussed and a calculated efficiency of 2% in the whole TEG system is obtained. Possible suggestions to further improve this type of generator in the future are given.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

In recent years, increased consumption of fossil fuels has induced many serious environmental and energy problems such as ozone depletion, global warming, atmospheric pollution and worldwide energy shortage etc. Rowe [1] reported that thermo-electricity, considered to be a kind of green and flexible source of electricity, had attracted great attention. Since the 1950s when the semiconductor materials with small band gap were found, more and more researchers have been engaged in these materials, because of their better thermoelectric performance than pure metals [2]. With many merits such as approximate 100,000 h steady-state operation, precise temperature control, a wide range of adaptability, and extraordinary reliability and longevity [3], TEG was initially used to provide power for spacecraft by National Aeronautics and Space Administration of USA in 1961. After the energy crisis in the 1970s, researches on thermoelectric power generation are always the focus all over the world [2]. At present, with the increasing gap between limited supply and increasing demand of power, researches on waste heat recovery by TEG have become crucial. The available waste heat sources include recover-able industrial heat-generating process, the exhausted waste heat of transportation vehicles, solar energy, combustion of solid waste and geothermal energy and so on [4].

Industrial waste heat takes a major part of the waste energy in the whole society. Hendricks et al. reported that 33% of the manufacturing industrial energy was released directly to the atmosphere or cooling systems as waste heat, because many industries were not able to recycle the excessive energy. They also pointed out that a range of 0.9 TWh to 2.8 TWh of electricity might be produced by waste heat each year if thermoelectric materials with average ZT (Z: figure-of-merit of thermoelectric materials, T: absolute operating temperature of thermoelectric materials) values ranging from 1 to 2 were available [5]. In addition, extremely large amounts of waste heat energy are generated from inefficient transportation vehicles. Generally speaking, cooling system is required to guarantee the work of the engine, because of the thermal limit of automotive engine. Typically, heat produced by automotive engine is removed by cooling loop which is full of coolant (water, oil) primarily, then dissipates to the ambient through air cooling [6]. Yu and Chau [7] pointed out that as for internal combustion engine, only 25% of the energy generated by fuel combustion was used to run vehicle, while 40% of the energy was discarded with exhausted gas, 30% of the energy was rejected through coolant, and 5% of the energy was dissipated as friction. Except that, harvesting solar energy based on TEG is another

* Corresponding author. Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, PR China. Tel.: +86 10 82543765; fax: +86 10 82543767.
E-mail address: jliu@mail.ipc.ac.cn (J. Liu).

important way to capture low-temperature heat. A typical TEG driven by solar power consists of a thermal collector, thermoelectric generator and groups of flow pipes. In this type of TEG, thermal collector is used to absorb heat from the solar radiation, then the heat is carried to thermoelectric generator by flow pipes. Building Scientific Research Center (BSRC) [8] presented a new concept of roof design named "The Thermoelectric Roof Solar Collector (TE-RSC)", which was comprised of thermoelectric modules, a rectangular fin heat sink, a copper plate, a transparent acrylic sheet and air gap. Research results indicated that about 1.2 W power could be obtained by such generator with 10 thermoelectric modules in 0.0525 m^2 surface area, under a solar radiation intensity of about 800 W/m^2 at ambient temperature between 30 and 35 °C. Though the electrical conversion efficiency of TE-RSC system was reported as low as 1−4%, this kind of generator is still popular in remote areas or some special fields.

Nowadays, TEG plays an even more significant role in recovering the waste heat. Nonetheless, the application of TEG is limited in a small domain where the cost is not the main issue to be considered, because of the low energy conversion efficiency of thermoelectric devices and units. In this paper, a new kind of TEG based on liquid metal was proposed as an effective way in harvesting the waste heat. Under the conception of this type of TEG, a demonstrating experiment for two different working conditions with low and high flow rates of liquid metal was carried out respectively, which indicated the feasibility of the new methods. Furthermore, the TEG performance characteristics are also discussed in detail.

2. Conceptual experiment

2.1. Basics of TEG based on liquid metal for waste heat recovery

Although various types of thermoelectric devices have been presented so far, many serious issues still exist, which mainly include low generating efficiency, short life span, low reliability, high cost and the like [9]. In order to solve these problems, improving the performance of thermoelectric material is one significant approach. Since the Seebeck effect was discovered in 1821, many different kinds of thermoelectric materials have been developed gradually [10−12]. Besides, improving the working performance of the waste heat carrier is also extremely critical for enhancing efficiency of the whole device on system level. So far, liquid metal is used as a type of coolant for heat dissipation of electronic devices because of the properties of high thermal conductivity, low melting points, non-flammable, non-toxic

activities, high boiling point and liquidness at normal temperature [13,14]. In this case, liquid metal can be an available alternative to harvest the waste heat for thermoelectric modules. Therefore a new kind of TEG based on liquid metal is proposed here. In the new TEG system, liquid metal serves as an efficient carrier of waste heat. Meanwhile, an electromagnetic pump is employed to circulate the liquid metal in such TEG system. Furthermore, in order to make the TEG system work better, cooling measures for the cool side of thermoelectric modules is also needed. The detailed structure of TEG based on liquid metal is introduced in the experimental part of this paper.

2.2. Experimental setup

The schematic diagram of the present TEG system based on liquid metal is shown in Fig. 1. This test system mainly consists of waste heat source, electromagnetic pump, TEG unit and a data acquisition system. Driven by electromagnetic pump, liquid metal which is heated by waste heat source, firstly flows through the electromagnetic pump then to liquid metal heating plate, and finally turns back to waste heat source as a circulation. In this case, waste heat simulated by the heat produced by electrical heaters is first taken away by liquid metal through heat convection process, and then it reaches liquid metal heating plate. After that, the waste heat passes through the liquid metal heating plate to the hot side of the TE modules. Finally, part of the heat is converted into electricity by the TE modules and the remaining waste heat is transferred through the TE modules and water-cooling plates then dissipated into the surrounding environment. In this experiment, in order to relieve the deformation caused by thermal stress, one stainless steel bellows with a length of 110 mm and 8 mm in diameter is employed to connect liquid metal heating plate with electromagnetic pump, while another stainless steel bellows with a length of 160 mm and 8 mm in diameter is used for connecting waste heat source with electromagnetic pump. The specific function, form and feature of each main part of the experimental setup are depicted as follows.

Ten electrical heating sticks (electrical heaters), each with power rating of 250 W, act as the waste heat source which provides heat to liquid metal through a corrosion-resistant plate with the size of 150 mm × 100 mm × 27 mm. At three millimeters above the electrical heaters in this stainless steel plate, there is a U-shaped channel for liquid metal with 10 mm in diameter and 315 mm in length. Hence, heat produced by heaters is transferred to liquid metal through the 3 mm thick corrosion-resistant plate which
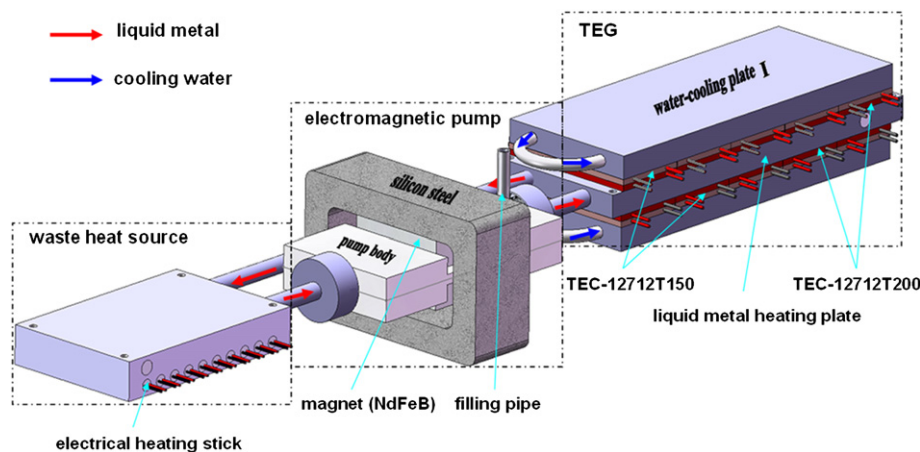

Fig. 1. Schematic of TEG based on liquid metal.

exists between electrical heaters and the U-shaped channel. In addition, electromagnetic pump applied in this system is composed of a pump body, magnet (NdFeB), silicon steel and two electrodes, respectively. The electromagnetic pump body with 200 mm × 90 mm × 30 mm in size is fixed between waste heat source and TEG unit, which is made of polytetrafluoroethylene (PTFE). In order to form a close magnetic loop and produce an enhanced magnetic field, silicon steel is used to conduct the magnetic flux. Moreover, two electrodes made of stainless steel are responsible for providing electric power to the electromagnetic pump. In the channel of electromagnetic pump, two baffle plates are designed to avoid contact between liquid metal with positive and negative electricity outside the magnetic field. In addition, a filling hole is designed on the top half body of electromagnetic pump for pouring liquid metal into TEG system.

TE modules, liquid metal heating plate, water-cooling plates I and II are the main components of TEG unit. Both the two water-cooling plates in TEG unit, made of aluminum material, have two parallel through-holes with 8 mm in diameter along the length direction of the plate for cooling water, the size of each water-cooling plate is 270 mm × 100 mm × 16 mm. Furthermore, there are two types of TE modules: one works at 200 °C as the maximum operating temperature, model TEC-12712T200; The other works at 150 °C, model TEC-12712T150. Both these two kinds of modules with size of 50 mm × 50 mm × 3.8 mm have a matrix of one hundred and twenty-seven thermoelectric couples (p-type and n-type) with Bi–Te material. The total forty TE modules are sandwiched between liquid metal heating plate and water-cooling plates in terms of four separate layers, so each layer includes ten TE modules. Ten TEC-12712T200 modules as one layer are placed on the top surface of liquid metal heating plate, while ten TEC-12712T150 modules as another layer sandwiched between TEC-12712T200 modules and water-cooling plate I. Between the lower surface of liquid metal heating plate and water-cooling plate II, there are the other two layers of TE modules which share the same structure with the first two layers. It is worth noting that all the hot sides of TEC-12712T200 modules are close to liquid metal heating plate while all the cool sides are close to the hot sides of TEC-12712T150 modules, and all the cool sides of TEC-12712T150 modules are close to water-cooling plates I and II. Moreover, in order to minimize the thermal contact resistance, all the contact surfaces are spread with heat conductive silicone grease, such as the surfaces between two kinds of TE modules, liquid metal heating plate and TEC-12712T200 modules, water-cooling plates and TEC-12712T150 modules respectively. In addition, liquid metal heating plate which is 270 mm × 100 mm × 16 mm in size has a U-shaped channel with 10 mm in diameter and 520 mm in length for liquid metal.

In this experiment, 164 ml (1.04 kg) $Ga_{66}In_{20.5}Sn_{13.5}$ liquid metal with melting point around 10.3 °C was adopted as the heat carrier. In addition, the flow velocity of cooling water is approximately 1000 ml/min during the whole process of this experiment. Moreover, four T-type thermocouples are placed at liquid metal heating plate, waste heat source, water-cooling plates I and II respectively, and one voltage transducer placed at TE modules. The temperature of each part of TEG system and voltage of TE module are measured by Agilent data acquisition system, model 34970A, USA.

3. Results

The total 40 TE modules were divided into 5 groups which were connected in parallel, while each group had 8 TE modules connected in series. In this experiment an external electric circuit was applied, which was composed of four LEDs (each of them with nominal power of 30 W), a resistance of 1 Ω and the TE modules. In the circuit, total 120 W LEDs and 1 Ω resistance played as a load, in which the 1 Ω resistance was used as a tool to measure the current, while TE modules served as the power source. The photograph of prototype of the liquid metal based TEG is illustrated as Fig. 2.

3.1. Experimental results under low volume flow of liquid metal

The volume flow of liquid metal is at a low level when the working current of electromagnetic pump is 10 A. Fig. 3 shows the temperature changes of waste heat source, liquid metal heating plate, water-cooling plates I and II and voltage of TE modules,
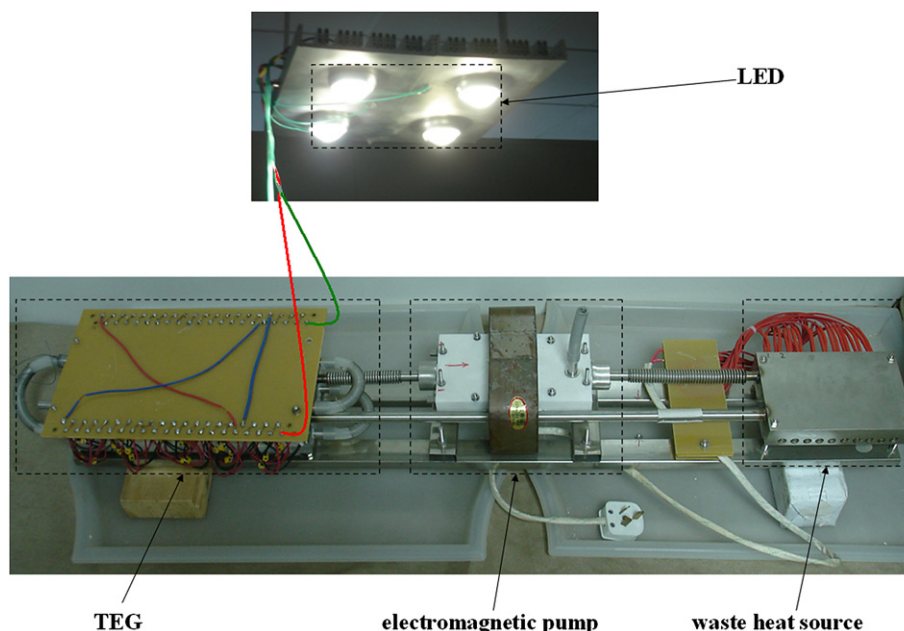

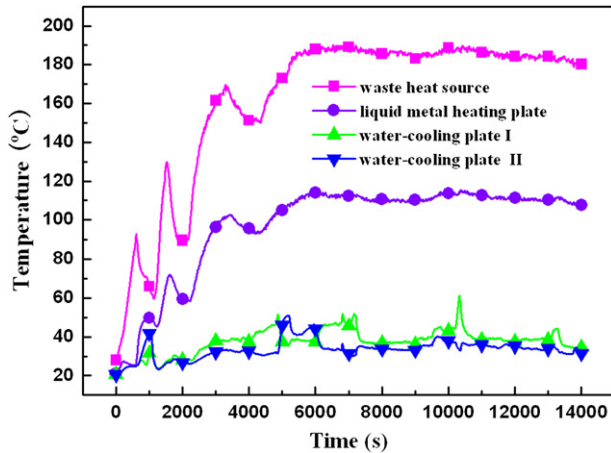**Fig. 2.** Photograph of prototype of the liquid metal based TEG.

Fig. 3. Changes of temperature of waste heat source, liquid metal heating plate, water-cooling plates I and II, respectively.

Fig. 5. Changes of temperature gap between liquid metal heating plate and water-cooling plates and variation of voltage of TE modules with time, respectively.

respectively. From this figure one could conclude that the temperature of liquid metal heating plate changes with the temperature of waste heat source, and it is always lower than that of waste heat source. Furthermore, changes of the temperature gap between liquid heating plate and water-cooling plate I (ΔT_{L-CI}) and that between liquid heating plate and water-cooling plate II (ΔT_{L-CII}) are illustrated in Fig. 4. It can be observed that changes of ΔT_{L-CI} follows the changes of ΔT_{L-CII} as a whole, while the maximum temperature difference between ΔT_{L-CI} and ΔT_{L-CII} is as big as 20 °C which will surely lead to different voltages produced by TE modules placed at the top and lower surfaces of the liquid metal heating plate. The main reason of this big temperature difference is the different cooling efficiencies on the cool sides of TE modules, which is due to different cooling water flow rates. When the temperature of waste heat source gets close to a balanced point, changes of ΔT_{L-CI}, ΔT_{L-CII} and variation of voltage of TE modules against time are shown as Fig. 5. One can get that the change of voltage of TE modules follows on the heels of variation of the temperature gap between liquid metal heating plate and water-cooling plates (ΔT_{L-C}), moreover, the highest output voltage of TE modules reaches 23.09 V when the waste heat source temperature gets to a balanced temperature near 190 °C. Obviously, according to Figs. 3–5, it is undoubted that TEG based on liquid metal for waste heat recovery is feasible.
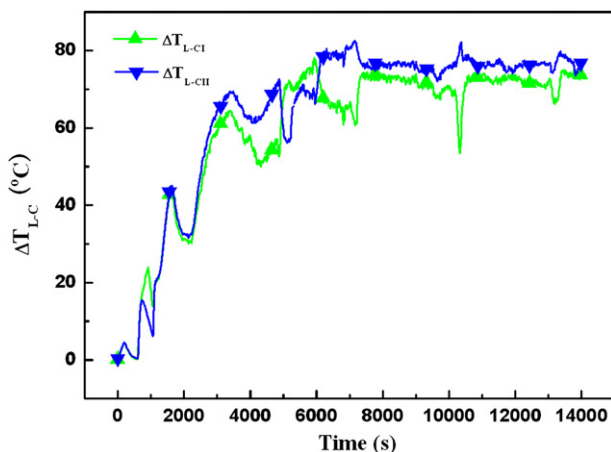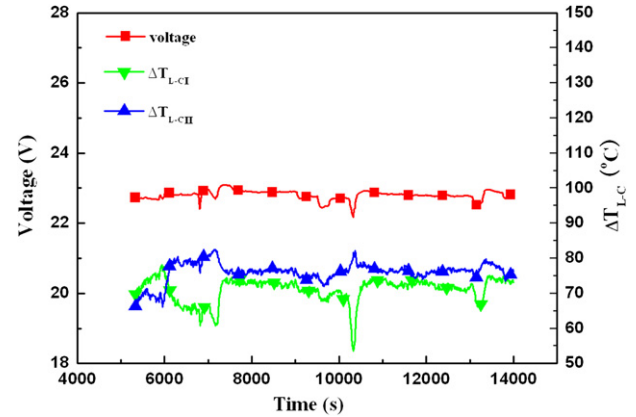
3.2. Experimental results under high volume flow rate of liquid metal

When the working current of electromagnetic pump is increased to 60 A, a high volume flow of liquid metal is gained. The temperature variations of waste heat source, liquid metal heating plate, water-cooling plates I and II and the changes of voltage of TE modules are illustrated as Fig. 6. It could be observed that the temperature of liquid metal heating plate changes with waste heat source and is also lower than the temperature of waste heat source as Fig. 3 shows. Fig. 7 gives the changes of temperature gap between liquid heating plate and water-cooling plates. Compared with Fig. 4 the difference between ΔT_{L-CI} and ΔT_{L-CII} is smaller, the maximum temperature gap is less than 5 °C, which indicates that high volume flow of liquid metal would decrease the temperature gap between ΔT_{L-CI} and ΔT_{L-CII}. Fig. 8 explains the changes of ΔT_{L-CI} and ΔT_{L-CII} and variation of voltage of TE modules against time. In this figure the voltage-changing tendency of TE modules is similar to that of ΔT_{L-CI} and ΔT_{L-CII}. Fig. 9 reveals the variation of voltage of TE modules with the temperature of liquid metal heating plate, water-cooling plates I and II respectively. This figure shows that as long as the temperature is in the safe scope, the TE modules could work better if the temperature of liquid metal heating plate is higher while the water-cooling plate is lower. From Figs. 8 and
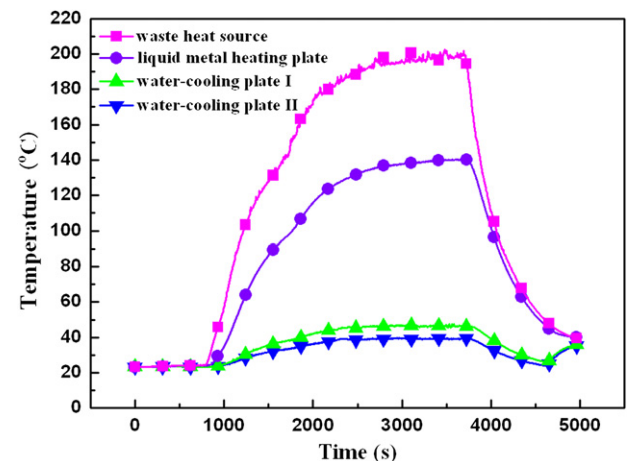

Fig. 4. Changes of temperature gap between liquid metal heating plate and water-cooling plates, respectively.

Fig. 6. Changes of temperature of waste heat source, liquid metal heating plate, water-cooling plates I and II, respectively.
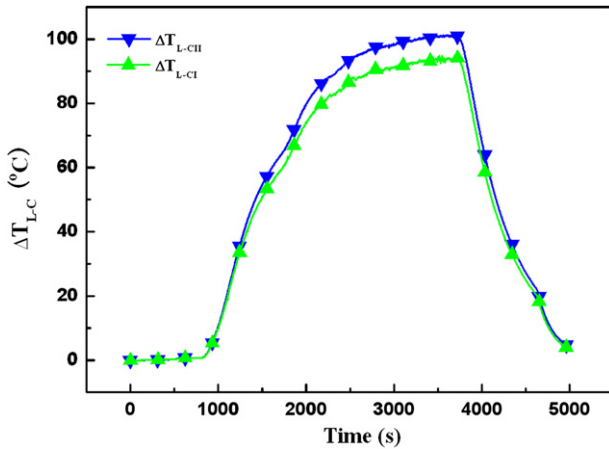
Fig. 7. Changes of temperature gap between liquid heating plate and water-cooling plates respectively.
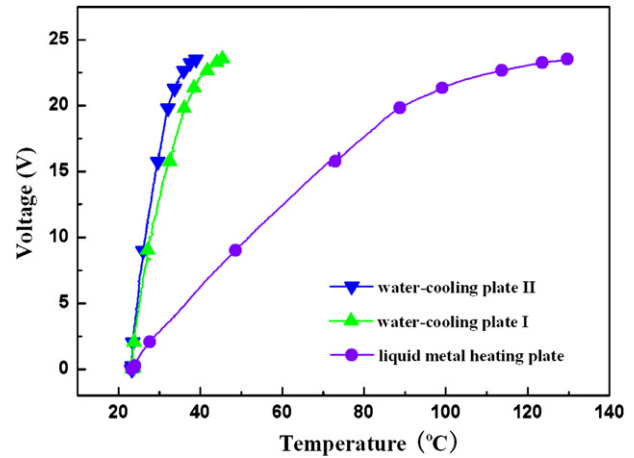

Fig. 9. The variation of voltage of TE modules with the temperature of liquid metal heating plate, water-cooling plates I and II respectively.

9 it can be found that enlarging the temperature gap between liquid metal heating plate and water-cooling plates can make TE modules work better. So the heat loss along the process of liquid metal transmission is one of the significant factors which influence the performance of the TEG based on liquid metal. In detail, available ways to cut down the heat loss include enhancing the flow rate of liquid metal which mainly depended on the working condition of electromagnetic pump, employing better thermal insulation material along transmission pipe which connected waste heat source to liquid metal heating plate, decreasing the flow resistance of the channels for liquid metal and so on.

Fig. 10 illustrates changes of voltage of TE modules through the whole experimental process. In Fig. 10, there are two peaks, the first output voltage peak is 33.14 V and the second one is 34.67 V. It should be pointed out that the first peak is caused by disconnecting the four LEDs from TE modules. And the voltage value of TE modules at the failing edge of the first peak is resulted from using the four LEDs and a 5 Ω resistance together as a new load instead of the foregoing one. When the circuit was open again, the voltage value of the second peak appeared. Then after changing the 5 Ω resistance for a 10 Ω one, the voltage value of TE modules is shown as the failing edge of the second peak. From the test data of Fig. 10, it can be concluded that TEG based on liquid metal for waste heat recovery can run steadily and the load connected to TE modules influences the output voltage.
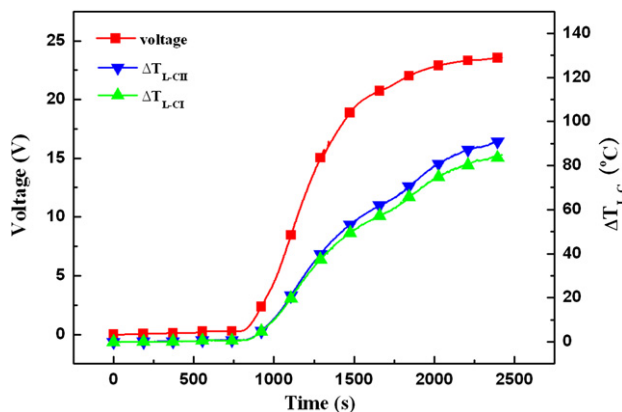
4. Discussion

4.1. Theoretical analysis of thermoelectric conversion of TEG

The maximum efficiency of thermoelectric conversion of TEG is defined as Eq. (1):

$$\eta_{\max} = \frac{T_{\text{hot}} - T_{\text{cold}}}{T_{\text{hot}}} \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_{\text{cold}}}{T_{\text{hot}}}} \qquad (1)$$

$$ZT = \frac{S^2}{\rho\lambda}T \qquad (2)$$

where, Z is figure-of-merit, $T(K)$ is absolute operating temperature, $S(\text{V K}^{-1})$ is the Seebeck coefficient, $\rho(\Omega\text{ m})$ is the electrical resistivity, $\lambda(\text{W m}^{-1}\text{ K}^{-1})$ is the coefficient of thermal conduction of the thermoelectric material, $T_{\text{cold}}(K)$ is the temperature of cool side of TE modules and $T_{\text{hot}}(K)$ is the temperature of hot side of TE modules [15]. A high efficiency of TEG can be obtained by increasing the Carnot efficiency ($\eta_c = T_{\text{cold}} - T_{\text{hot}}/T_{\text{hot}}$). According to Eq. (1), in fact, the temperature difference between cooling plate and liquid metal heating plate of TEG unit is required to be as big as possible. In addition, the figure-of-merit of thermoelectric material should be
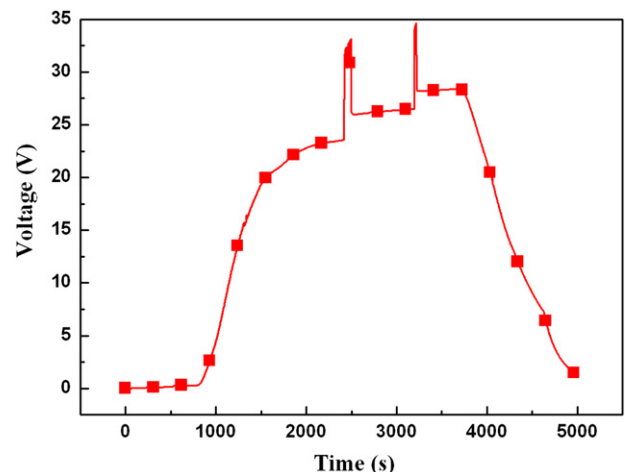

Fig. 8. Changes of temperature gap between liquid metal heating plate and water-cooling plates and variation of voltage of TE modules with time.

Fig. 10. Changes of voltage of TE modules with time.

high, that is, high Seeback coefficient and electrical conductivity but low thermal conductivity. In the whole device the main thermal resistances ($R_{thermal}$) include conductive thermal resistance ($R_{conductive}$) and convective thermal resistance ($R_{convective}$):

$$R_{conductive} = \frac{L}{\lambda A_1} \tag{3}$$

$$R_{convective} = \frac{1}{hA_2} \tag{4}$$

where L is the thickness of the conductive plate, λ is the thermal coefficient of the material, A_1 is the cross-sectional area of conductive plate, where the cross-section is perpendicular to the direction of heat flow, h is the convective heat transfer coefficient, A_2 is the heat transfer area. In this experimental setup, $R_{conductive}$ exists when heat transfers from the heaters to the internal wall of pipe or channel for liquid metal and from the internal wall of pipe or channel for liquid metal to TE modules. Besides, $R_{convective}$ exists when heat transfers from liquid metal to the internal wall of pipe or channel for liquid metal. In order to reduce the heat loss during the process of taking the heat from the waste heat source to the liquid metal heating plate, both of the $R_{conductive}$ and $R_{convective}$ should be increased, in other words, effective thermal insulation measures should be taken during the transportation of waste heat. However, when liquid metal absorbs heat from waste heat source and releases it to liquid metal heating plate, and heat transfers between TE modules and liquid metal heating plate, both the $R_{convective}$ and $R_{conductive}$ should be decreased to make the heat to be utilized adequately.

The efficiency of the whole liquid metal based TEG system depends on the efficiency of heat transmission from waste heat source to the plate heated by the liquid metal and the efficiency of the TE modules. It can be written as:

$$\eta_{TEG\_system} = \frac{Q_E}{Q_W} = \frac{Q_{L\_H}}{Q_W} \times \frac{Q_E}{Q_{L\_H}} = \eta_{LM} \times \eta_{TE} \tag{5}$$

where η_{TEG_system}, η_{LM} and η_{TE} are the efficiency of TEG system, heat transmission from waste heat source to liquid metal heating plate and the TE module respectively. Q_E, Q_{L_H} and Q_W are respectively the electric energy produced by TE modules, the thermal energy harvested by liquid metal heating plate and the thermal energy of the waste heat source. Therefore, when liquid metal worked under high volume flow, the efficiency of the TEG is calculated as:

$$\eta_{TEG\_system\_H} = 66\% \times 3\% = 2\% \tag{6}$$

Although the efficiency of TEG based on liquid metal as tested in this paper is higher than 1.66% which was proposed to harvest waste heat exhausted from automobile [16] in 2008, the liquid metal based TEG still does not perform very well. The main reasons resulting in the mediocre performance of a liquid metal based TEG are as follows: There was no heat insulation material arranged along the pipes between the waste heat source and the liquid metal heating plate, which led to part of the heat leakage to the surroundings during the transport process. The conversion efficiency of TE modules adopted in this experiment was lower compared with the conventional ones (3%–6.5%) [15].

4.2. Preliminary interpretation

First, liquid metal based TEG for waste heat recovery is feasible and available. Second, the output voltage of TE modules is dependent on the temperature gap of ΔT_{L-CI} and ΔT_{L-CII}. It is when in the safe range of TE modules that big temperature difference between

liquid metal heating plate and water-cooling plates is beneficial for output voltage. Third, the temperature gap between waste heat source and liquid metal heating plate (ΔT_{S-L}) is one key factor influencing the performance of this TEG system, which means that better heat conductivity of waste heat source and liquid metal heating plate does make sense to improve system performance. It can be seen in Figs. 11 and 12 that, the balanced temperature gap between waste heat source and liquid heating plate is 74.89 °C when electromagnetic pump operating current is 10 A, and 58.47 °C when the current increased to 60 A. From these figures one can conclude that the operating current of electromagnetic pump is one influencing factor of the heat loss from waste heat source to liquid metal heating plate, thus optimizing the performance of electromagnetic pump is a significant way to make TEG system work better. In addition, in order to reduce the heat loss along the transmission of liquid metal, measures of heat insulation and the flow-resistance reduction of channels for liquid metal are also required. Furthermore, to save water, a fan could be used to cool the TE modules instead of using cooling water in future work. Moreover, additional performance parameters of this type of TEG system should be measured to analyze its performance, such as the temperature difference between liquid metal input and output ports in each unit, effects of flow rate of liquid metal and so on. Besides, in order to make an in depth research on liquid metal based TEG, a great number of experimental measurements and numerical simulations should be implemented in the future, which include: (a) seeking new liquid metal with low melting point; (b) improving the arrangement of the thermoelectric modules; (c) hunting for a new thermoelectric material with high efficiency; (d) using computer simulation to optimize the design of TEG system based on liquid metal or part of it; and (e) reducing the cost of TEG based on liquid metal.

4.3. Advantages and disadvantages of liquid metal based on TEG for waste heat recovery

Distinctive superiorities of the liquid metal based TEG are as follows: (a) Without moving parts and materials that may require periodic replenishment, TEG based on liquid metal is reliable. (b) Less maintenance is demanded by TEG based on liquid metal because of no noise and vibration. (c) Getting together all of the TE modules, liquid metal heating plate makes the TGE unit compact and less position-dependent. (d) With the help of liquid metal based TEG, long-distance energy transportation is efficiently
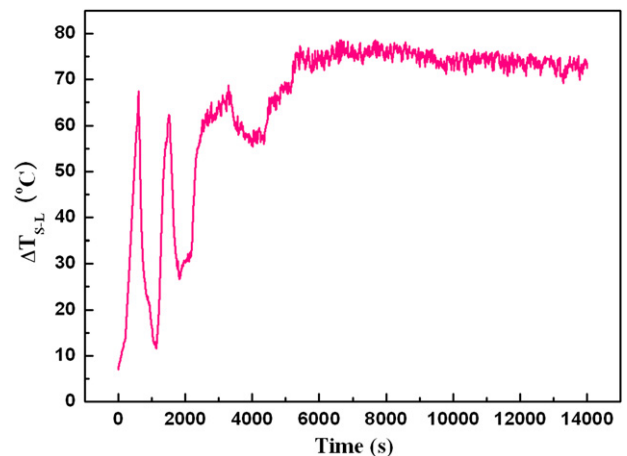
Fig. 11. Changes of temperature gap between waste heat source and liquid metal heating plate when the operating current of electromagnetic pump is 10 A.
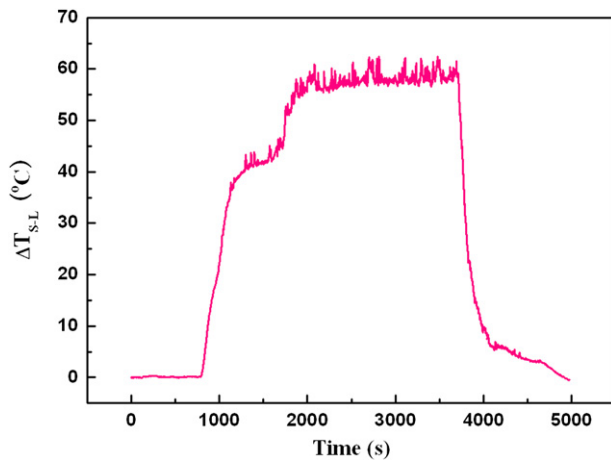
Fig. 12. Changes of temperature gap between waste heat source and liquid metal heating plate when the operating current of electromagnetic pump is 60 A.

achieved. (e) TEG based on liquid metal has characteristics of energy conservation and environmental protection. (f) TEG based on liquid metal is so flexible that it can be applied in various areas.

Although there are many merits of TEG based on liquid metal, it also has a few drawbacks which need to be improved in future study such as: (a) Even though the thermal conductivity of liquid metal is high, it is difficult for the liquid metal based TEG to harvest all the waste heat. (b) The electromagnetic pump used to drive liquid metal needs to consume part of the power. (c) Limited by the property of the thermoelectric material, the thermoelectric conversion efficiency of TE modules is not high enough. (d) Problems of leakage and corrosion induced by liquid metal should be considered seriously. More advanced optimization designs on TEG system based on liquid metal are in great demand for further development.

5. Conclusions

In this study, both technical concept and basic features of the liquid metal based TEG for waste heat recovery were presented and investigated. A prototype system was successfully built up and adopted to evaluate the new electricity generation strategy. According to the experimental measurement, the TEG using liquid metal to convert waste heat into electricity is highly feasible and flexible, which promises its bright future in a wide variety of energy saving situations. Although some defects still exist in the present working system, it opens the way of using room temperature liquid metal to fully harvest and utilize low-grade heat.

References

[1] Rowe DM. Thermoelectrics, an environmentally-friendly source of electrical power. Renewable Energy 1999;16(1–4):1251–6.
[2] Xi H, Luo L, Fraisse G. Development and applications of solar-based thermoelectric technologies. Renewable and Sustainable Energy Reviews 2007;11: 923–36.
[3] Ewert MK. Terrestrial and aerospace solar heat pump development: past, present and future, In: ASME Paper at solar' 98, Albuquerque, NM; 1998.
[4] Ono K, Suzuki RO. Thermoelectric power generation: converting low-grade heat into electricity. Journal of the Minerals, Metals and Materials Society 1998;50(12):49–51.
[5] Hendricks T, Choate WT. Engineering scoping study of thermoelectric generator systems for industrial waste heat recovery. Washington, D.C.: Industrial Technologies Program, U.S. Department of Energy; 2006. pp. 1–76.
[6] Hugues LT, Asfaw B. Heat recovery from automotive engine. Applied Thermal Engineering 2009;29:439–44.
[7] Yu C, Chau KT. Thermoelectric automotive waste heat energy recovery using maximum power point tracking. Energy Conversion and Management 2009; 50(6):1506–12.
[8] Maneewan S, Khedari J, Zeghmati B, Hirunlabh J, Eakburanawat J. Investigation on generated power of thermoelectric roof solar collector. Renewable Energy 2004;29:743–52.
[9] Zhao J, Zhu D, Zhou Z, Wang C, Chen H. Research progress of thermoelectric power generation. Chinese Journal of Power Sources 2010;34(3):310–3.
[10] Ohta H, Kim SW, Mune Y, Mizoguchi T, Nomura K, Ohta S, et al. Giant thermoelectric Seebeck coefficient of a two-dimensional electron gas in $SrTiO_3$. Nature Materials 2007;6:129–34.
[11] Snyder GJ, Toberer ES. Complex thermoelectric materials. Nature Materials 2008;7:105–14.
[12] Hsu KF, Loo S, Guo F, Chen W, Dyck JS, Uher C, et al. Cubic $AgPb_mSbTe_{2+m}$: bulk thermoelectric materials with high figure of merit. Science 2004; 303(5659):818–21.
[13] Ma KQ, Liu J. Heat-driven liquid metal cooling device for the thermal management of a computer chip. Journal of Physics D: Applied Physics 2007; 40:4722–9.
[14] Deng YG, Liu J. A liquid metal cooling system for the thermal management of high power LEDs. International Communications in Heat and Mass Transfer 2010;37:788–91.
[15] Fleurial JP. Thermoelectric power generation materials: technology and application opportunities. Journal of the Minerals, Metals and Materials Society 2009;61(4):79–85.
[16] Saqr KM, Mansour MK, Musa MN. Thermal design of automobile exhaust based thermoelectric generators: objectives and challenges. International Journal of Automotion Technology 2008;9(2):155–60.